Per. Mineral. (2002), *71*, 3, 289-303 http://go.to/permin

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY, ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

Provenance of stones employed in building the Badia Morronese (L'Aquila, Italy)

VINCENZO FERRINI[1]*, SILVANO MIGNARDI[1] and ANNA COLANGELO[2]

[1] Dipartimento di Scienze della Terra, Università di Roma "La Sapienza", P.le Aldo Moro, 5 – 00185 Roma (Italy)
[2] Soprintendenza per i Beni Architettonici e per il Paesaggio per il Patrimonio Storico, Artistico e Demoantropologico dell'Abruzzo, L'Aquila (Italy)

Submitted, July 2002- Accepted, November 2002

ABSTRACT. — Mineralogical, petrographic, paleontological and geochemical studies were carried out to characterize the limestone used as the building stone of the Badia Morronese (XIII century A.D.) near Sulmona (L'Aquila, Italy). Comparison between 19 samples from the monument and 63 samples of formations outcropping around the Valle Peligna, collected from documented, recognizable or suspected quarries and natural outcrops, revealed that the building stone show petrographic characters and fossil content similar to those of the *Calcari Cristallini* Fm (Upper Cretaceous-Paleocene). The provenance of the stone for the monument from quite small areas is supported by the homogeneity of determined trace element contents and carbon and oxygen isotopic compositions, which are substantially close to those of samples collected at Colle Mitra (Sulmona).

RIASSUNTO. — È stato eseguito uno studio mineralogico, petrografico, paleontologico e geochimico finalizzato alla caratterizzazione delle rocce calcaree utilizzate nella costruzione della Badia Morronese (XIII sec.), presso Sulmona (L'Aquila). Il confronto tra 19 campioni del monumento e 63 campioni delle formazioni affioranti nelle aree circostanti la Valle Peligna, prelevati da antiche cave, presunte zone di estrazione ed affioramenti naturali, ha dimostrato che le rocce usate nel monumento hanno caratteri petrografici e contenuto fossilifero simili a quelli dei litotipi della formazione dei «Calcari Cristallini» (Cretacico superiore – Paleocene). La provenienza delle rocce utilizzate nella costruzione del monumento da aree piuttosto ristrette circostanti la Valle Peligna, è suggerita dalla omogeneità dei tenori degli elementi in traccia determinati e dalla composizione isotopica di carbonio ed ossigeno, che sono sostanzialmente simili a quelli dei campioni raccolti a Colle Mitra (Sulmona).

KEY WORDS: *Monument stone, petrography, geochemistry, provenance, Sulmona, Italy*

* Corresponding author, E-mail: vincenzo.ferrini@uniroma1.it

INTRODUCTION

By means of mineralogical-petrographic and geochemical studies combined with microscopy analysis on facies and fossils, this paper defines the provenance of limestone used in building the Badia Morronese (XIII century A.D.) near Sulmona (L'Aquila, Italy), one of the most important monuments in the Valle Peligna (Fig. 1). Results of comparative study of samples from the monument and from formations outcropping around the Valle Peligna showing high degree of similarity to the former, identify the provenance of the stone. The results of this study may also be viewed as a preliminary data-bank for the limestone of this area of the Central Apennines, of which mineralogical-petrographic and geochemical data in the literature are scarce. This information may contribute to better understanding of the depositional environment of limestone, as trace element contents (Ni, Co, Cu, Zn), widely used as indicators of paleoenvironmental conditions, and the carbon and oxygen isotopic compositions of the main representative carbonate facies outcropping in the area, were also determined.

GEOLOGICAL SETTING AND SAMPLING

The area in which the Badia Morronese is located belongs to the eastern sector of the Central Apennines and comprises the Meso-Cenozoic carbonate ridges extending around the Valle Peligna (Mt. Maiella, Mt. Morrone, Mt. Genzana, Mt. Prezza) (Fig. 2).

The following successions outcrop in this area (e.g. Colacicchi and Praturlon, 1965 a, b; Angelucci and Praturlon, 1968; Colacicchi, 1967; Accordi *et al.* 1986; Liberatore, 1998; Pianu, 1999):

a) Limestone and dolostone in the carbonate-platform domain (Late Triassic-Early Liassic), including massive greyish-white dolostone with a relict texture of shelf limestone and cherty nodules with lamellibranchs and gastropods (Dolomie di Castelmanfrino Fm, Lias-Dogger).

b) Limestone in the carbonate-platform domain (Liassic *p.p.*-Paleocene), including dolomitic laminated mudstone with inter-supratidal structures (Monte Acquaviva equivalente Fm, Upper Cretaceous-Paleocene); ooid or skeletal packstone and grainstone of inner shoal or beach (Morrone di Pacentro Fm, Dogger-Lower Cretaceous); calcareous and dolomitic mudstone with benthic foraminifers (Terratta s.s. Fm, Dogger-Lower Cretaceous). Sixteen samples of the Terratta Fm were collected from the outcrops at the quarry at Cave di Introdacqua.

c) Carbonate successions in the ramp domain

Fig. 1 – The Badia Morronese Complex.

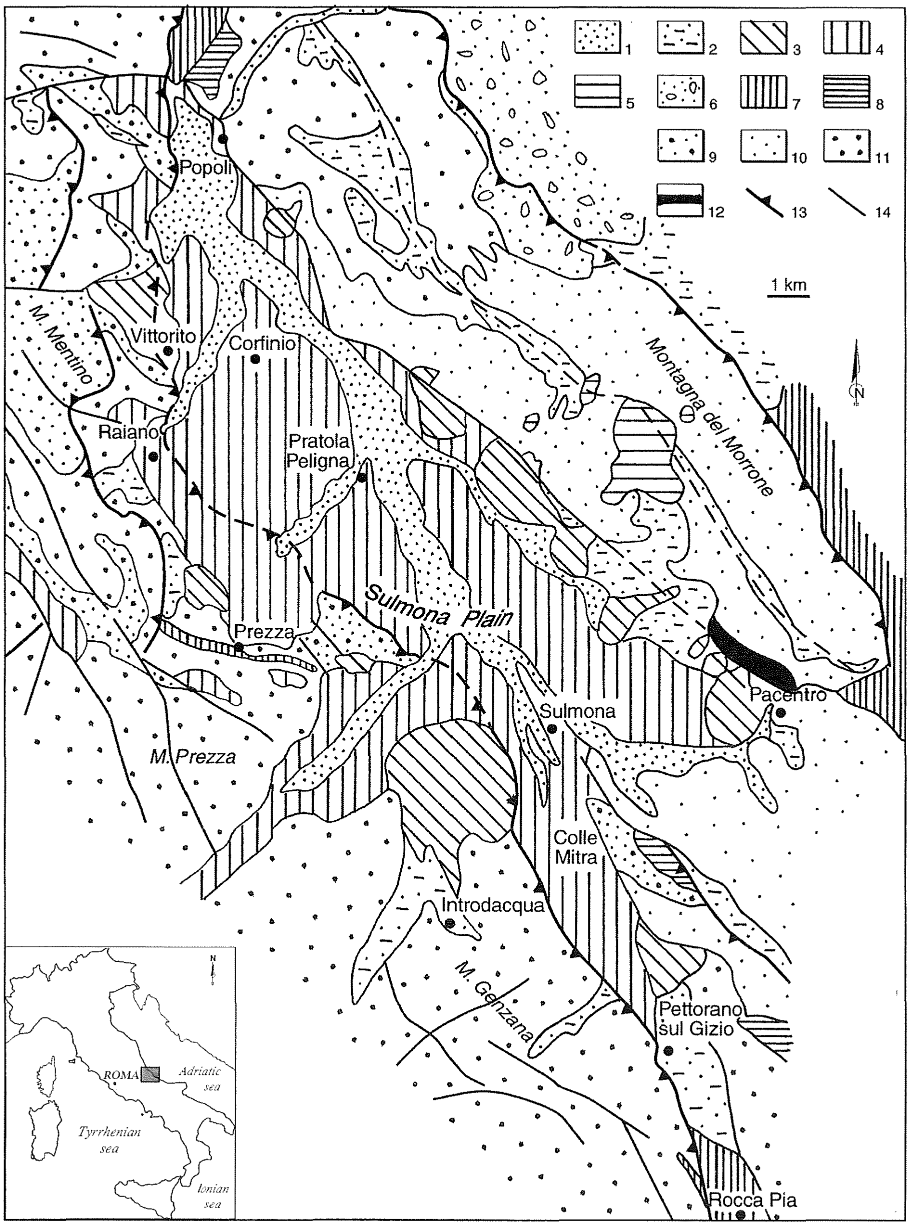

Fig. 2 – Geological sketch map of the Sulmona area (simplified after Accordi et al., 1986). 1 = recent alluvial deposits including conglomerates and sands (Upper Pleistocene-Holocene); 2 = taluses, landslides (Pleistocene-Holocene); 3 = talus, talus fans including cemented conglomerates and breccias (Pleistocene-Holocene); 4 = alluvial deposits, sands and conglomerates (Pleistocene); 5 = taluses and talus fans more or less cemented, slope breccias (Lower Pleistocene); 6 = conglomerates and breccias (Pliocene); 7 = clayey-sandy successions (Upper Miocene); 8 = carbonate successions in slope domain (Miocene); 9 = carbonate successions in ramp domain (Cretaceous-Paleocene); 10 = carbonate successions in platform domain; 11 = limestone in carbonate-platform domain (Liassic-Paleocene); 12 limestone and dolostone in the carbonate-platform domain (Late Triassic-Early Liassic); 13 = thrust faults; 14 = faults.

(Liassic p.p.-Eocene), including densely packed skeletal grainstone with rudist and echinoid remains, interbedded with siltstone and mudstone layers with planktonic foraminifers (Calcari Cristallini Fm, Upper Cretaceous-Paleocene); pelagic mudstone and marly mudstone, mudstone and cherty levels interbedded with shale and fine biodetrital grainstone (Scaglia bianca e rossa Fm, Monte Acquaviva *p.p.* Fm, S. Spirito *p.p.* Fm, Upper Cretaceous-Middle Eocene); well-bedded white mudstone with intercalations of chert (Maiolica Fm, Upper Jurassic-Lower Cretaceous); mudstone with pelagic pelecypods, nodular marly mudstone and wackestone (Calcari a *Filaments* Fm, Rosso Ammonitico Fm, Upper Liassic-Upper Jurassic); stratified microbioclastic mudstone with radiolarians, sponge spicules and benthic foraminifers (Corniola Fm, Middle Liassic). Forty-seven samples of the Calcari Cristallini Fm were collected from quarries and natural outcrops near the localities of Pietre Regie di Colle Mitra (Sulmona, 26 samples), Prezza (5 samples), Costa S. Venanzio (Raiano, 7 samples), Rava del Peschio (Vittorito, 5 samples) and Fosso di Fontenuova (Chieti, 4 samples).

d) Carbonate successions in the slope domain (Paleocene-Oligocene), formed of packstone and grainstone with pelagic and benthic fauna (Calcari a Briozoi e Litotamni Fm, Middle Miocene); packstone and grainstone interbedded with marly planktonic mudstone (S.S. Spirito *p.p.* Fm, Bolognano *p.p.* Fm, Eocene-Oligocene).

e) Clayey-sandy successions in the slope domain (Upper Miocene-Lower Pliocene), forming pelitic and sandy successions.

f) Continental successions (Pleistocene-Holocene) of taluses and talus fans, alluvial deposits and travertine.

THE BADIA MORRONESE

The Badia Morronese is located about 4 kilometres from Sulmona. As it stands now, the Abbey appears as a grandiose, monumental unit of great artistic and historic value on a rectangular layout (about 119 by 140 metres) (Fig. 1). Surrounded by massive walls, the edifice was planned around three courtyards and is subdivided – both horizontally and vertically – by a series of convenient passageways and staircases leading to the different rooms which have remained mostly intact throughout the centuries.

Fig. 3 shows the planimetry of the Badia, together with the location of samples. The courtyards are reached through a majestic portal flanked by two Doric columns characterized by an alternation of drums with circular and square sections. They are respectively built of whitish calcarenitic lithotypes and blocks of polymictic breccia with reddish calcareous cement.

The most worth mentioning areas of the Abbey are the courtyards, the stairs leading to the upper floors, the church with the Caldora Chapel, the old refectory, the old pharmacy and the library.

Among the still standing parts characterized by historic and artistic value and which we can still admire, we should like to mention the interesting façade of the Church in the Borromini taste, which recalls the church of San Carlo alle Quattro Fontane in Rome, the sixteenth-century bell tower similar to the contemporary one of the church of the SS. Annunziata (Sulmona), as well as the church built on a Greek cross plan. Above the crossing of the naves, the cupola rests on four Corinthian columns. The interior, simple and bright, is decorated with precious stalls and furnishing of the seventeenth century.

The Caldora Chapel, one of the still surviving parts of the Abbey, adjacent to the Church, deserves special attention. It includes what remained of the pre-existent small church dedicated to the Virgin Mary, and contains works of art such as the Caldora-Cantelmi sarcophagus, sculpted by Gualtiero d'Alemagna in 1412, and a precious series of frescoes depicting episodes from the life of Christ, going back to the first half of the fifteenth century. A fundamental work in the

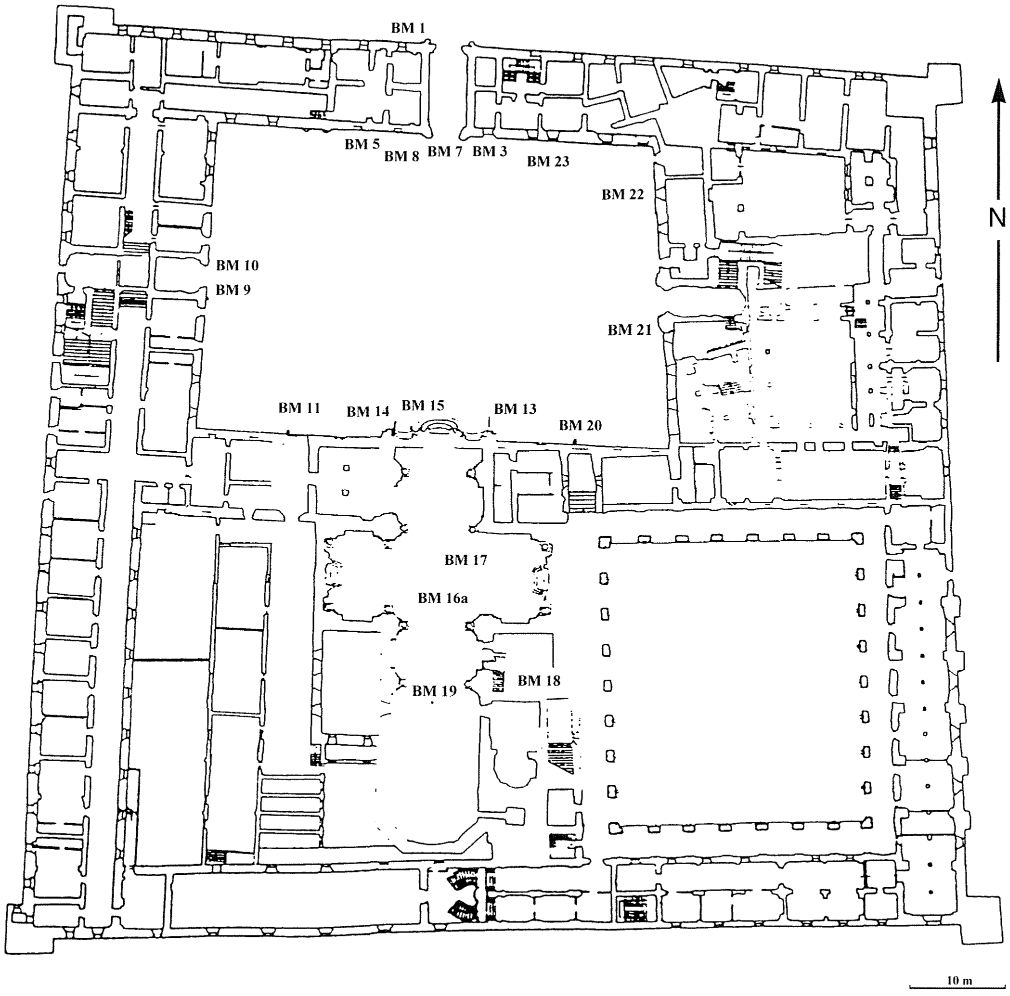

Fig. 3 – Plan of *Badia Morronese*, showing sample locations. Sample BM19 was taken from a column in crypt.

history of the Abruzzo painting, these frescoes have been attributed to an interesting artist called the Master of the Caldora Chapel. Under the apse, is a large, mediaeval crypt, with an irregular plan and cylindrical columns decorated by unusual capitals.

In the past centuries, the Abbey represented the richest and most renowned monastery of the Congregation of the Celestini, to such an extent that it became the seat of the Chief Abbot of that order, as well as the frame of reference for religious, cultural and lay life of the whole region. The Badia was built on one flank of Mt. Morrone around 1241 by the Friar Pietro di Angelerio from Isernia, who became pope as Celestino V. He first enlarged an ancient chapel dedicated to Santa Maria del Morrone and later promoted the building of a new church with an adjacent monastery, dedicated to the Holy Spirit. Soon it became the richest and the most famous monastery of the Congregation, and a general assembly of the order held there in September 1293 even stated that the Badia Morronese should become the seat of the Chief Abbot of the Celestini. During Celestino V's reign many privileges were bestowed upon the Badia: in particular, Charles II of Anjou donated land and castles thus making of it one of the most remarkable abbeys of his kingdom. The Badia complex steadily thrived over the years and created the opportunity for flourishing religious, lay and moral culture. Enlarged and transformed in the sixteenth century, it was also restored after the devastating earthquake of 1706. Before it was suppressed, it boasted a financial income of over six thousand ducats per year and was populated by no less than eighty monks. As a consequence of the suppression of the order in 1807, the edifice was used first as a hospice and then as a prison.

ANALYTICAL PROCEDURES

Nineteen samples of fragments and chips from the archaeological site of the Badia Morronese and 63 hand samples of formations outcropping around the Valle Peligna were selected for optical and chemical analysis. The latter samples were collected from documented, recognizable or suspected quarries and natural outcrops. Table 1 lists the type and lithology of samples from the archaeological site.

Petrographic, sedimentological and paleontological characterization of the samples was carried out by microscopy in transmitted polarized light.

The samples, being previously completely dissolved by $HC1O_4$+HF attack, were analysed by atomic absorption spectrometry using a Perkin Elmer spectrophotometer for determination of CaO, MgO, FeO, MnO, Na_2O, K_2O BaO, Li, Rb, Sr, Pb, Zn, Cu, Co, Ni and Cd contents.

The C and O isotopic compositions of 8

TABLE 1

Samples analysed from the Badia Morronese.

Sample	Typology	Lithology
BM1	3rd drum of the right column of the front	Packstone
BM3	windowsill of the 1st right window in the court	Packstone
BM5	windowsill of the 1st left window in the court	Packstone
BM7	threshold of the inner door of the 1st court	Packstone
BM8	1st right ashlar of the door	Packstone
BM9	2nd left ashlar of the door	Packstone
BM10	3rd right ashlar of the door	Packstone
BM11	2nd right ashlar of the door	Packstone
BM13	base of the 2nd left column of the front	Grainstone
BM14	3rd right ashlar of the door	Grainstone
BM15	base of the 1st right column of the front	Grainstone
BM16a	base of the holy water font	Grainstone
BM17	block of the floor of the left chapel	Grainstone
BM18	1st right ashlar of the portal of the crypt	Grainstone
BM19	2nd left column of the crypt	Grainstone
BM20	1st right ashlar of the door	Grainstone
BM21	windowsill	Packstone
BM22	windowsill	Packstone
BM23	base of the 1st left ashlar of the door	Packstone

samples from the monument and 26 samples from the formations showing macroscopic characteristics similar to the former were determined by standard methods at Geochron Laboratories (USA). Values are reported in ‰ with reference to the Peedee Formation Bellemnite (PDB) standard for carbon; oxygen isotope data are reported relative to the Standard Mean Ocean Water (SMOW) standard. Analytical precision was generally ± 0.02‰ for carbon and ± 0.12‰ for oxygen.

Results and discussion

Petrographic characteristics and provenance of stone

The samples from the Badia Morronese are packstone poorly sorted with isopachous fibrous cement, and grainstone with good sorting. Fossils are represented by *Orbitoides*, *Goupillaudina*, *Omphalocyclus* and nodosariidae. Echinoderm fragments are common. In particular, packstones BM7 and BM8 and grainstones BM15 and BM19 contain large amounts of echinoderm and mollusc fragments. Instead, packstone BM21 has no bioclasts but it is characterized by many veinlets filled with sparitic calcite.

The samples of the studied formations are grainstone and packstone, grain-supported with poor to good sorting and with isopachous fibrous cement. Because of their petrographic characteristics and fossil contents, the samples from Colle Mitra, Prezza, Costa S. Venanzio, R. del Peschio and Fosso di Fontenuova belong to the Calcari Cristallini Fm and those from Cave di Introdacqua to the Terratta Fm.

On the basis of the petrographic characters and fossil content the stone used to built the Badia Morronese may be ascribed to the Calcari Cristallini Fm.

Geochemical characteristics

Table 2 shows the contents of elements in samples from the Badia Morronese and Table 3 the averages and ranges of the contents of elements in the formations. Na, Mn, Fe and Sr were selected for analysis because of their significance in carbonate sedimentation and diagenesis (Janaway and Parnell, 1989; Calvo *et al.*, 1995). Other elements such as Li, K and Rb, considered diagnostic in carbonate sedimentation (e.g. Calvo *et al.*, 1995; Dini *et al.*, 1998), and Ni, Co, Zn and Cu, widely used to obtain paleo-environmental information (e.g. Jones and Manning, 1994; Sighinolfi and Tateo, 1998), were also analysed.

Fig. 4a shows that the samples from the archaeological site of the Badia Morronese have average contents of all analysed major and minor elements close only to those from the Calcari Cristallini Fm from Colle Mitra. In addiction, the figure shows that the latter have lower average MgO contents than all the analysed samples, whereas those of the same formation from Prezza, R. del Peschio and Fosso di Fontenuova and those from the Terratta Fm from Cave di Introdacqua are distinguished by their MnO, Na_2O and K_2O contents. These characteristics probably reflect different amounts of dolomite and clay in the samples.

The Badia Morronese samples have average contents of all analysed trace elements similar and generally close only to those from the Calcari Cristallini Fm from Colle Mitra (Fig. 4b). On the basis of similar trace element contents, the samples are gathered into three groups: 1) Colle Mitra and Cave di Introdacqua; 2) Costa S. Venanzio, R. del Peschio and Prezza, except for Rb and Cu contents; 3) Fosso di Fontenuova, which shows Sr, Li, Rb, Pb and Ni contents different from all the other samples.

Contents of Li, Rb, Pb, Ni and, to a lesser extent, Co, discriminate among the samples. Fig. 5a demonstrates that Li, Rb and Pb contents in the samples from the Badia Morronese are different from those of the Calcari Cristallini Fm from Prezza, R. del Peschio, Costa S. Venanzio and Fosso di Fontenuova, whereas their contents are close to those of the Terratta Fm from Cave di Introdacqua and the Calcari Cristallini Fm from Colle Mitra. Instead, Fig. 5b shows that Pb, Ni and Co contents cannot discriminate either

TABLE 2

Major, minor (wt%) and trace (ppm) element contents and C and O isotopic composition (‰) of samples from the Badia Morronese. Fe_2O_3 as totale Fe.

Sample	BM1	BM3	BM5	BM7	BM8	BM9	BM10	BM11	BM13	BM14	BM15	BM16a	BM17	BM18	BM19	BM20	BM21	BM22	BM23
CaO	55.30	55.22	55.62	55.29	55.14	55.47	55.49	55.74	55.64	55.04	55.58	55.32	55.80	55.38	55.56	55.40	55.28	55.30	55.33
MgO	0.20	0.08	0.16	0.20	0.07	0.16	0.25	0.09	0.18	0.19	0.28	0.22	0.23	0.21	0.10	0.21	0.21	0.12	0.17
Fe_2O_3	0.004	0.004	0.005	0.003	0.004	0.003	0.002	0.003	0.004	0.003	0.017	0.018	0.006	0.005	0.004	0.042	0.004	0.004	0.004
MnO	0.004	0.004	0.003	0.006	0.003	0.004	0.005	0.003	0.003	0.006	0.007	0.003	0.004	0.004	0.004	0.003	0.005	0.005	0.004
Na_2O	0.049	0.046	0.053	0.054	0.045	0.073	0.065	0.045	0.057	0.057	0.051	0.037	0.065	0.062	0.048	0.066	0.054	0.064	0.074
K_2O	0.020	0.010	0.020	0.010	0.020	0.020	0.010	0.020	0.010	0.020	0.020	0.020	0.010	0.020	0.020	0.010	0.010	0.010	0.020
BaO	0.022	0.019	0.018	0.015	0.022	0.014	0.021	0.017	0.020	0.020	0.020	0.021	0.021	0.021	0.015	0.021	0.020	0.018	0.017
Li	22	25	22	20	22	22	22	23	24	23	23	22	28	23	19	21	24	29	25
Rb	36	34	36	37	35	35	33	25	37	32	34	36	36	36	36	39	36	33	38
Sr	168	139	175	157	147	146	137	158	151	130	134	144	147	163	167	138	142	160	147
Pb	75	91	95	86	75	88	79	80	87	95	84	76	91	78	100	77	85	90	76
Zn	13	9	26	10	20	8	20	11	9	15	10	23	7	13	24	17	12	11	10
Cu	11	12	13	9	6	13	8	12	11	9	7	8	12	9	7	7	9	13	6
Co	19	23	18	19	24	19	22	20	23	19	18	20	22	24	19	21	23	24	19
Ni	32	34	26	33	27	39	30	27	34	29	34	37	33	36	34	34	35	36	30
Cd	16	13	20	15	15	15	14	14	12	14	16	16	11	19	17	16	15	10	13
Cr	8	7	5	5	7	5	1	4	7	1	7	5	1	7	1	8	5	5	9
$\delta^{13}C$	1.7			1.6	1.5						1.4	1.0			0.6	0.9		-0.5	
$\delta^{18}O$	29.1			31.1	31.1						30.5	29.5			30.5	29.4		29.3	

TABLE 3

Averanges and ranges of major, minor (wt.%) and trace (ppm) element contents and C and O isotopic composition (‰) of samples from some formations outcropping in Sulmona area.
CM = Colle Mitra, IN = Cave di Introdacqua, F = Fosso di Fontenuova, P = Prezza, V = R. del Peschio, S = Costa S. Venenazio, n = number of samples. Fe_2O_3 as total Fe.

	CM n = 26		IN n = 16		F n = 4		P n = 5		V n = 5		S n = 7	
CaO	55.48±0.22	55.04-55.84	55.23±0.21	54.88-55.48	55.36±0.05	55.27-55.39	54.98±0.16	54.77-55.17	55.15±0.33	54.71-55.45	54.68±0.08	54.55-54.80
MgO	0.18±0.06	0.07-0.28	0.38±0.06	0.31-.47	0.46±0.02	0.43-0.48	0.40±0.04	0.35-0.43	0.39±0.05	0.32-0.44	0.41±0.04	0.75-0.98
Fe_2O_3	0.007±0.009	0.002-0.042	0.013±0.017	0.005-0.015	0.038±0.051	0.006-0.114	0.010±0.001	0.009-0.012	0.020±0.003	0.017-0.025	0.009±0.001	0.008-0.010
MnO	0.004±0.001	0.003-0.007	0.004±0.001	0.003-0.005	0.004±0.002	0.004-0.005	0.042±0.008	0.003-0.005	0.002±0.001	0.001-0.002	0.002±0.001	0.001-0.003
Na_2O	0.060±0.011	0.037-0.074	0.099±0.028	0.080-0.120	0.060±0.003	0.053-0.060	0.020±0.006	0.017-0.031	0.020±0.007	0.009-0.027	0.020±0.007	0.009-0.025
K_2O	0.020±0.002	0.010-0.020	0.066±0.036	0.010-0.120	0.070±0.004	0.070-0.080	0.010±0.004	0.010-0.020	0.010±0.003	0.010-0.020	0.010±0.004	0.010-0.020
BaO	0.019±0.003	0.014-0.022	0.041±0.001	0.019-0.050	0.048±0.002	0.046-0.049	0.025±0.002	0.022-0.027	0.024±0.001	0.023-0.025	0.024±0.001	0.022-0.025
Li	22±2	19-25	26±1	25-28	17±1	17-18	10±2	7-12	7±2	5-9	8±2	4-10
Rb	35±3	30-39	40±2	36-42	26±4	22-13	49±10	38-61	61±8	51-71	76±6	68-81
Sr	148±16	117-175	111±11	90-127	343±18	322-360	162±4	158-167	152±6	144-159	146±13	121-161
Pb	87±9	75-101	86±7	74-94	21±7	17-31	49±13	32-68	50±4	45-55	50±6	41-57
Zn	14±6	7-26	11±2	9-16	20±2	18-22	16±4	10-21	20±3	17-25	21±2	17-25
Cu	10±2	6-13	11±2	9-15	12±1	12-13	38±3	35-41	10±2	8-13	13±2	9-16
Co	20±2	18-24	20±2	17-23	23±1	21-23	5±3	1-7	6±2	3-8	5±2	2-7
Ni	32±4	26-37	28±1	26-30	19±1	17-20	12±2	10-14	14±2	12-16	13±2	11-17
Cd	16±2	13-20	8±1	7-9	8±1	6-9	4±1	3-5	5±2	3-7	6±3	2-10
Cr	5±3	1-9	8±2	5-10	4±2	1-6	3±1	1-4	2±1	1-6	3±1	1-5
	n = 6		n = 6		n = 2		n = 3		n = 3		n = 2	
$\delta^{13}C$	1.1±0.3	0.6/1.5	1.7±0.8	0.9/3.1	-0.4±0.4	-0.1/-0.6	2.7±0.4	2.3/3.1	1.9±0.6	1.2/2.3	2.2±0.1	2.1/2.2
$\delta^{18}O$	30.4±0.7	29.4/31.2	29.8±0.6	29.1/30.5	29.1±0.1	29.1/29.2	30.6±0.1	30.5/30.7	30.0±0.2	29.8/30.1	31.1±0.1	31.0/31.1

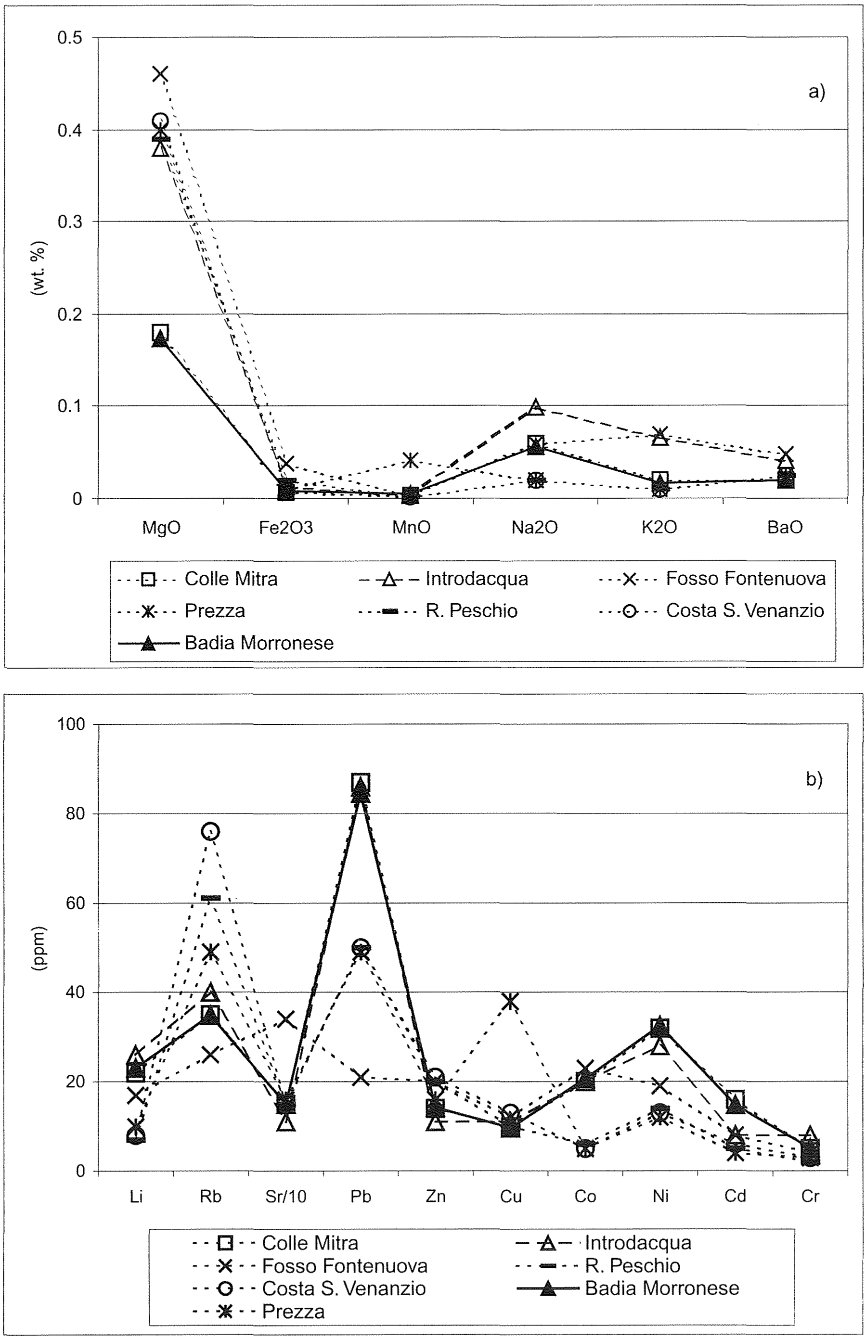

Fig. 4 – Major and minor (a) and trace element (b) contents of samples from Badia Morronese and some formations outcropping in Sulmona area.

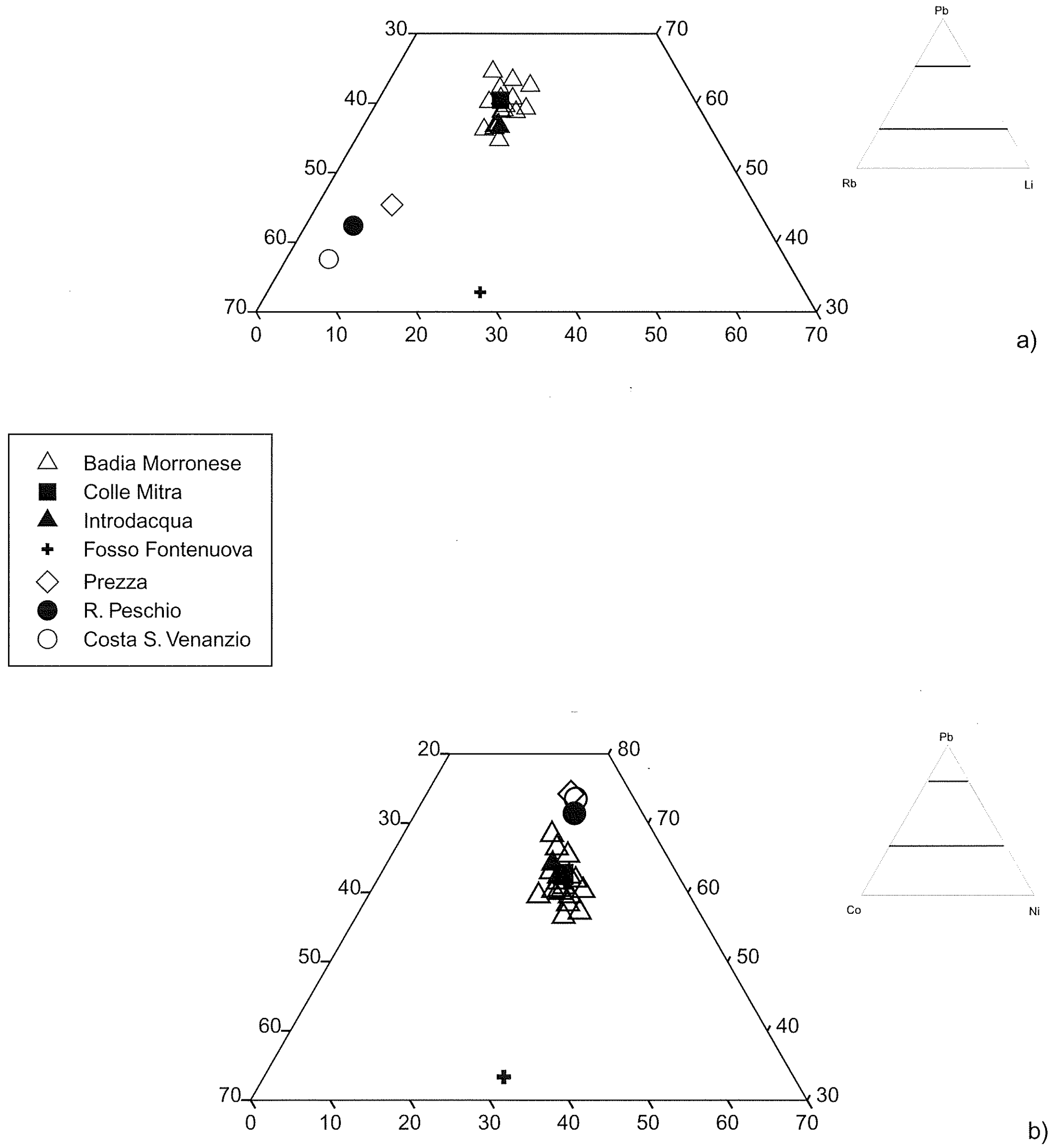

Fig. 5 – Pb-Rb-Li (a) and Pb-Co-Ni (b) relationships. Average contents of samples from formations are also shown.

archaeological samples or those of the formations.

Carbonate geochemistry may be considered a rather conservative parameter in diagenetic processes, resulting important in yielding paleo-environmental indications (Renard, 1986). In particular, Sr content is considered a helpful tool in understanding the origin and diagenesis of carbonates (Kinsman, 1969; Veizer *et al.*, 1971; Calvo *et al.*, 1995), since calcareous-dolomitic samples generally contain less Sr than calcarenitic ones. This behaviour fits the fact that Sr substitutes for Ca rather than Mg in the dolomite lattice (Behrens and Land, 1972; Veizer and Domovic, 1974; Kretz, 1982) and that the distribution coefficients for Sr in dolomite are much lower than one (Jacobson and Usdowski, 1976; Katz and Matthews, 1977).

The Sr contents of our samples deserve some further comments as, according to current findings (Renard, 1979, 1986), the Sr/Mg ratio may be used as a paleo-environmental indicator. In neritic and coastal environments, the Sr and Mg contents of carbonates exhibit a positive trend, whereas in pelagic environments they show an inverse correlation. In the samples of the formations, Sr correlates positively with Mg (r = 0.87), suggesting that both were deposited in shallow water in the coastal platform domain, fitting geological and paleontological features of typical facies of this environment.

Other significant elements yielding paleo-environmental information are redox-sensitive trace elements (V, Cr, Ni, Co, Zn, Cu), which are widely used as indicators of paleo-environmental conditions at the sea bottom (Jones and Manning, 1994). In particular, the Ni/Co ratio is considered an index of paleo-oxygenation conditions. In our samples, the values of the ratio are < 5, indicating that the sediments were deposited under an oxic water column.

Taking into account the relative Ni and Co enrichment of the monument samples and those of the Calcari Cristallini Fm from Colle Mitra and Fosso di Fontenuova, the samples of the Terratta Fm from Cave Introdacqua with respect to those of the Calcari Cristallini Fm from Prezza, Costa S. Venanzio and R. del Peschio, it may be assumed that the former group were deposited in more reducing (although still oxic) conditions than the latter group.

An alternative hypothesis is that, after sediment deposition, element redistribution took place. This process, occurring during diagenesis or weathering, is well-known (Buckley and Cranston, 1988; Condie *et al.*, 1995). Element remobilisation usually occurs towards redox boundaries, and the fixing of mobilised elements is controlled by a redox-sensitive diagenetic phase (e.g., pyrite and other sulfides). Element redistribution may take place if sufficient organic matter and time are available to allow full redistribution, and if redox-sensitive elements are in a form which allows their transport. As organic matter is the main source of redox-sensitive elements (Piper, 1988), its destruction by oxidizing reactions causes mobilisation of elements in dissolved ionic form in interstitial fluids. Thus, fixing of Ni and Co is controlled by the presence of reduced sulfur and, if sulphide compounds undergo oxidation processes, part of the elements remains dissolved in seawater or is removed by interstitial fluids.

We believe that the different distributions of Ni and Co in the studied samples reflect different paleo-oxygenation conditions in the sedimentary basin, although element redistribution during diagenesis cannot be excluded.

ISOTOPE GEOCHEMISTRY

Isotopic analyses were carried out to highlight possible geochemical similarities or differences among the samples. The oxygen and carbon isotopic compositions of the samples (Tables 2 and 3) fall in the field of typical marine limestone (Keith and Weber, 1964), ranging from –0.5 to +1.7‰ for $\delta^{13}C$ and from +29.1 to +31.1‰ for $\delta^{18}O$. The samples with higher $\delta^{18}O$ values (BM7, BM8, BM15, BM19) are those containing larger

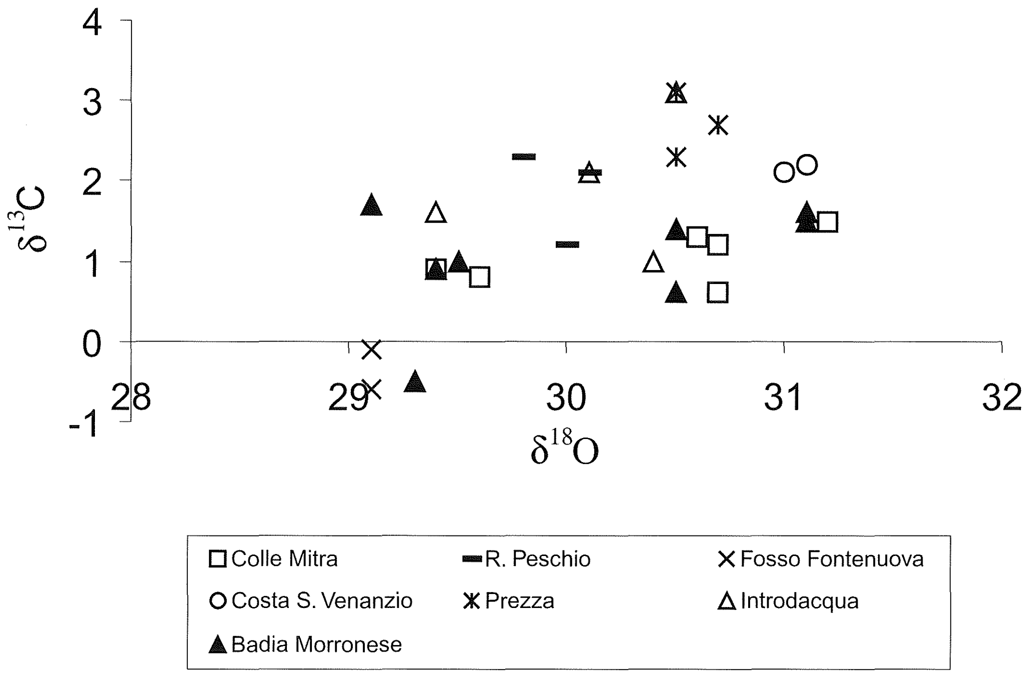

Fig. 6 – $\delta^{13}C$-$\delta^{18}O$ cross-plot of studied samples.

amounts of bioclasts (mainly echinoderm and mollusc fragments). Sample BM21 has a negative $\delta^{13}C$ value, being characterized by veinlets filled with sparitic calcite.

Fig. 6 shows the good fit between the isotopic compositions of the stone of the Badia Morronese and that from the Calcari Cristallini Fm, collected at Colle Mitra.

As regards the formations, Fig. 6 shows that samples of the Terratta and Calcari Cristallini Fms may generally be distinguished on the basis of their carbon and oxygen isotope ratios. Moreover, samples from different outcrops of the Calcari Cristallini Fm have different isotopic signatures, indicating either that the limestone formed in sedimentary subenvironments characterized by their own hydrochemistry, or that variations in isotopic composition took place during diagenesis and later history.

CONCLUSIONS

Comparative study of the petrographical, mineralogical, paleontological, geochemical and isotopic features of limestone samples from the Badia Morronese and from some outcrops of the Terratta and Calcari Cristallini Fms near Valle Peligna (L'Aquila, Italy) identified the provenance of the stone used to build the monument.

The Badia Morronese samples are packstone and grainstone which on the basis of petrographic characters and fossil content may be ascribed to the Calcari Cristallini Fm. The samples from Colle Mitra, Prezza, Costa S. Venanzio, R. del Peschio and Fosso di Fontenuova belong to the same formation, whereas those from Cave di Introdacqua come from the Terratta Fm.

The Badia Morronese samples have average contents of all determined major and minor elements close only to samples from the Calcari Cristallini Fm from Colle Mitra. Contents of Li, Rb and Pb distinguish the stone of the Badia Morronese from samples of the Calcari Cristallini Fm collected from Prezza, R. del Peschio, Costa S. Venanzio and Fosso di Fontenuova and show that they are compositionally similar to those collected from Colle Mitra.

Lastly, the provenance of stone from the abandoned quarry at Pietre Regie di Colle Mitra finds further support in the isotopic composition of the studied samples.

ACKNOWLEDGMENTS

This work was carried out within the Progetto Finalizzato «Beni Culturali» of the C.N.R.. Thanks are due to the Soprintendenza BAAS of L'Aquila for authorization to collect samples.

REFERENCES

ACCORDI G., CARBONE F., CIVITELLI G., CORDA L., DE RITA D., ESU D., FUNICIELLO R., KOTSAKIS T. and MARIOTTI G. and SPOSATO A. (1986) — *Lithofacies map of Latium-Abruzzi and neighbouring areas (scale 1:250,000).* C.N.R. - Progetto Finalizzato Geodinamica.

ANGELUCCI A. and PRATURLON A. (1968) — *Raddoppio della serie meso-cenozoica nelle Gole di Celano a Nord del Fucino (Appennino centrale).* Geologica Romana **7**, 431-446.

BEHRENS E.W. and LAND L.S. (1972) — *Subtidal Holocene dolomite, Baffin Bay, Texas.* J. Sediment. Petrol., **42**, 155-161.

BUCKLEY D.E. and CRANSTON R.E. (1988) — *Early diagenesis in deep-sea turbidites. The imprint of paleo-oxidation zone.* Geochim. Cosmochim. Acta, **52**, 2925-2939.

CALVO J.P., JONES B.F., BUSTILLO M., FORT R., ALONSO ZARZA A.M. and KENDALL C. (1995) — *Sedimentology and geochemistry of carbonates from lacustrine sequences in the Madrid Basin, central Spain.* Chem. Geol., **123**, 173-191.

COLACICCHI R. (1967) — *Geologia della Marsica orientale.* Geologica Romana, **6**, 189-316.

COLACICCHI R. and PRATURLON A. (1965a) — *Il problema delle facies nel Giurese della Marsica Nord-orientale.* Boll. Soc. Geol. It., **84**, 55-66.

COLACICCHI R. and PRATURLON A. (1965b) — *Stratigraphical investigations on the Mesozoic shelf-edge facies in the eastern Marsica (central Appennines, Italy).* Geologica Romana, **4**, 89-118.

CONDIE K.C., DENGATE J. and CULLERS R.L. (1995) — *Behaviour of rare earth elements in a paleoweathering profile on granodiorite in the Front Range, Colorado, USA.* Geochim. Cosmochim. Acta, **59**, 279-294.

DINI M., TUNIS G. and VENTURINI S. (1998) — *Continental, brackish and marine carbonates from the Lower Cretaceous of Kolone-Barbariga (Istria, Croatia): stratigraphy, sedimentology and geochemistry.* Paleogeogr. Paleoclimatol. Paleoecol., **14**, 245-269.

JACOBSON R.L. and USDOWSKI N.E. (1976) — *Partitioning of strontium between calcite, dolomite and liquidus.* Contrib. Mineral. Petrol., **59**, 171-185.

JANAWAY T.M. and PARNELL J. (1989) — *Carbonate production within the Orcadian Basin, northern Scotland: a petrographic and geochemical study.* Paleogeogr. Paleoclimatol. Paleoecol., **70**, 89-105.

JONES B. and MANNING D.A.C. (1994) — *Comparison of geochemical indices used for the interpretation of paleoredox conditions in ancient mudstones.* Chem Geol., **111**, 111-129.

KATZ A. and MATTHEWS A. (1977) — *The dolomitization of $CaCO_3$: an experimental study at 252-295°C.* Geochim. Cosmochim. Acta, **41**, 297-308.

KEITH M.L. and WEBER J.N. (1964) — *Carbon and oxygen isotopic composition of selected limestones and fossils.* Geochim. Cosmochim. Acta, **28**, 1787-1816.

KINSMAN D.J. (1969) — *Interpretation of Sr^{+2} concentrations in carbonate minerals and rocks.* J. Sediment. Petrol., **39**, 486-508.

KRETZ R. (1982) — *A model for the distribution of trace elements between calcite and dolomite.* Geochim. Cosmochim. Acta, **46**, 1979-1981.

LIBERATORE M.A. (1998) — *Caratterizzazione minero-petrografica e geochimica dei materiali litici utilizzati in alcuni monumenti della Valle Peligna per l'individuazione dei siti di provenienza: Complesso della S.S. Annunziata Sulmona e porte delle mura di cinta di Pettorano sul Gizio.* Degree thesis, University of Rome «La Sapienza», Italy, pp. 150.

PIANU M. (1999) — *I materiali litici del Santuario di Ercole Curino e del Complesso della Badia Morronese (Sulmona, AQ): caratterizzazione petrografica e geochimica finalizzata all'individuazione dei siti di provenienza.* Degree thesis, University of Rome «La Sapienza», Italy, pp. 191.

PIPER D.Z. (1988) — *The metal oxide fraction of pelagic sediment in the equatorial North Pacific Ocean: A source of metals in ferro-manganese nodules*. Geochim. Cosmochim. Acta, **52**, 2127-2145.

RENARD M. (1979) — *Aspect géochimique de la diagenèse des carbonates. Teneurs en strontium et en magnésium des carbonates: essai d'interprétation de l'inversion de la corrélation Sr-Mg observée dans les carbonates du domaine pélagique par rapport à ceux du domain néritique*. Bull. B.R.G.M. Sect. IV **2**, 133-152.

RENARD M. (1986) — *Pelagic carbonate chemostratigraphy (Sr, Mg, ^{18}O, ^{13}C)*. Mar. Micropaleontol., **10**, 117-164.

SIGHINOLFI G.P. and TATEO F. (1998) — *Mineralogical and geochemical criteria for distinguishing turbidite and hemipelagic pelites – the Maastrichtian pf the northern Apennines, Italy*. Sediment. Geol., **115**, 301-313.

VEIZER J. and DEMOVIC R. (1974) — *Strontium as a tool in facies analysis*. J. Sediment. Petrol., **44**, 1-100.

VEIZER J., DEMOVIC R. and TURAN J. (1971) — *Possible use of strontium in sedimentary carbonate rocks as a paleo-environmental indicator*. Sediment. Geol., **5**, 5-52.